Metallicity, planetary formation and migration

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ABSTRACT
Recent observations show a clear correlation between the probability of hosting a planet and the metallicity of the parent star. Since radial velocity surveys are biased, however, towards detecting planets with short orbital periods, the probability-metallicity correlation could merely reflect a dependence of migration rates on metallicity. We investigated the possibility, but find no basis to suggest that the migration process is sensitive to the metallicity. The indication is, therefore, that a higher metallicity results in a higher probability for planet *formation*.

Key words: accretion, accretion discs – planetary systems: formation – planetary systems: protoplanetary discs.

1 INTRODUCTION

Planet searches, mostly via radial velocity surveys of nearby stars, have so far yielded some 110 planets (e.g. Schneider 2003). The stars that are harboring planets have been known for some time to be relatively metal-rich (e.g. Gonzalez 1998, 1999; Gonzalez, Wallerstein & Saar 1999; Reid 2002). While some of the early studies suffered from clear selection effects, since the planet hunters tended to concentrate on metal-rich stars, more recent studies tend to be merely brightness limited. In particular, Fischer & Valenti (2003) examined 754 stars in the solar neighborhood and found that the probability of hosting a planet rises from about 5 per cent when the iron abundance is $\sim 1/3$ that of the sun, to about 20 per cent, when the iron abundance is ~ 3 times that of the sun. We will generally assume that the metal content of the stellar host reflects the metallicity of the planets/protoplanetary disc (although see Saumon et al. 1996). Suggestions have been made that the observed metallicity 'excess' may reflect 'pollution' of the star's convective envelope by the accretion of planets (e.g. Laughlin & Adams 1997; Conzalez 1998). If that were true, however, one would expect stars with shallow convection zones (e.g. F stars) to show correspondingly higher metallicity enhancements. Such an effect is not observed (Fisher & Valenti 2003).

Broadly speaking, there are two scenarios for planet formation. One scenario involves a multi-stage process, in which dust grains coagulate to form rocks, then planetesimals, and the latter coalesce to form planetary embryos that accrete the gaseous envelopes (e.g. Goldreich & Ward 1973; Pollack et al. 1996; Lissauer 2001). In the other scenario, giant planets form from the gravitationally collaps-

ing regions of unstable protoplanetary discs (e.g. Boss 2001; Mayer et al. 2002; Rice et al. 2003). On the face of it, the observed correlation between the metallicity of a star and its probability of hosting planets can be taken as supporting the multi-stage formation process. However, it should be realized that all the observed extrasolar planets (around main sequence stars) are believed to have migrated inward from larger radii (e.g. Lin, Bodenheimer & Richardson 1996; Armitage et al. 2002; Trilling, Lunine & Benz 2002), because planet formation at the observed radii appears to be difficult (e.g. Bodenheimer, Hubickyj & Lissauer 2000; Mayer et al. 2002). This raises the possibility, in principle, that the higher metallicity is required for the migration, rather than for the formation process (Sigurdsson et al. 2003). In the present Letter we examine this possibility.

2 MIGRATION AND METALLICITY

In order for the observed metallicity-planet frequency correlation to be an effect of migration alone, we need to explore the possibility that a low metallicity somehow inhibits migration. Mechanisms of migration that involve planet-planet scattering (e.g. Rasio & Ford 1996; Papaloizou & Terquem 2001) do not depend on the metallicity. The scattering of planetesimals by massive planets (e.g. Murray et al. 1998) does depend on the metallicity, but only if one requires the planetesimals to *form* via the multi-stage process. The only mechanism we need to study, therefore, is migration due to gravitational interaction with a gaseous, viscous, protoplanetary disc. The process we are interested in is "Type II" migration, in which the planet opens a gap in the disc, and subsequently follows its viscous evolution. We take the view that an observed Jupiter-sized planet is essentially the *last one* to have formed as the migration came to a halt (Ar-

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mitage et al. 2002; Trilling, Lunine & Benz, 2003). In this case, assuming that Jupiter-sized planets have to form close to, or beyond, a radius of ~5 AU, (e.g. Mayer et al. 2002; Boss 1995) we are interested in the properties of remnant discs at a time when the remaining mass of the disc was a few Jupiter masses at a radius of ~5 AU. If the disc is much more massive than this, then the subsequent evolution of the disc will sweep the planet into the star.

There are two obvious ways, in principle, in which migration can be significantly affected: (i) If the viscosity in the disc is reduced to extremely low values due to the MHD turbulence dying away, and (ii) if migration becomes significantly slower due to global changes in the disc structure. In what follows, we examine each of these possibilities in turn.

2.1   Dead zones

The viscosity in accretion discs most probably originates from the magneto-rotational instability (MRI; Balbus & Hawley 1991). Numerical simulations have shown that the MRI, and the concomitant MHD turbulence are suppressed when the magnetic Reynolds number is smaller than some critical value (Gammie 1996; Gammie & Menou 1998; Fleming, Stone & Hawley 2000). This leads in some parts of the disc to a layered disc structure, in which the gas near the disc mid-plane is cold, shielded from ionizing radiation and non viscous. Accretion then occurs only in a very thin surface layer that is ionized by cosmic rays.

In a shear flow, the magnetic Reynolds number is defined as

$$Rm = LV/\eta \ \ ,$$

where L and V are typical length and velocity scales, respectively, and η is the resistivity. Adopting $L \sim H$ (the disc half-thickness), $V \sim c_s$ (the speed of sound), as is appropriate for the simulations that make use of the shearing box approximation (e.g. Fleming et al. 2000), the requirement $Rm \lesssim Rm_{\rm crit}$ corresponds to balancing the growth rate of the MRI by Ohmic diffusion. When no externally imposed vertical magnetic field is present, the critical value is of order $Rm_{\rm crit} \sim 2000$ (Hawley, Gammie & Balbus, 1996). When one allows for an external vertical uniform field, $Rm_{\rm crit} \sim 100$ (Fleming et al. 2000). The decay of MHD angular momentum transport results in a "dead zone," in which the viscosity is very low, and migration might be expected either to stop or to be slowed down significantly. Of course, if the dead zone does not significantly change the rate of migration, then the effect of metallicity on the dead zone is not relevant to our current considerations. Since the Reynolds number depends on the resistivity, which, in turn, depends on the electron fraction, a change in the metallicity could lead to changes in the formation of a dead zone that could lead to changes in the properties of migration. The resistivity is given by (e.g. Matsumura & Pudritz 2003)

$$\eta = 234 \ T^{1/2}/x_e \ \text{cm}^2 \ \text{s}^{-1} \ \ ,$$

where T is the mid-plane disc temperature, and $x_e = n_e/n$ is the electron fraction (n_e and n are the number densities of electrons and neutral atoms respectively). Thus, at fixed x_e, since $H \propto c_s/\Omega$, where $\Omega \propto R^{-3/2}$ is the angular velocity of the disc, we have that

$$Rm \propto T^{1/2} R^{3/2} \ \ .$$

Matsumara & Pudritz (2003) consider the radiative, hydrostatic disc model developed by Chiang & Goldreich (1997), and Chiang et al. (2001). This model has an assumed surface density of the form

$$\Sigma = \Sigma_o (R/\text{AU})^{-3/2} \ \ ,$$

with a fiducial value of $\Sigma_o = 10^3 \ \text{g cm}^{-2}$ which gives a disc mass of a few Jupiter masses within about 5 AU. The flared, radiative equilibrium disc of Chiang & Goldreich (1997) has $T \propto R^{-3/7}$ for $R < 84$ AU. Assuming a state of ionization balance (where the ionization can be caused by either the central star or cosmic rays), and using the equation of the electron fraction given by Oppenheimer & Dalgarno (1974), Matsumura & Pudritz (2003) solved for the radius of the dead zone in the two limiting cases of no metals at all, $x_m = 0$, and essentially all metals ($x_m \gg x_e$), where x_m is metal fraction. Assuming a critical Reynolds number appropriate for a disc with a superimposed poloidal field (which they take to correspond to a critical Reynolds number $Rm_{\rm crit} = 1\text{--}10$), they found that even at these extremes, the radius of the dead zone differed by at most a factor ~2 (~1 AU in the metal dominant case, and ~2 AU in the no-metals case).

For the fiducial disc we see that $Rm \propto R^{9/7}$. Thus, if one increases the critical Reynolds number by a factor of ~20–100, as is inferred from simulations with no imposed poloidal field, and which is more likely to be the case for a protoplanetary disc at $R \sim 5$ AU, then the radius of the dead zone becomes *independent* of the metallicity, and is determined solely by the surface density ($\Sigma \sim 100 \ \text{g cm}^{-2}$) that allows for ionization by cosmic rays (Gammie 1996). In the disc model used by Matsumura & Pudritz (taken from Chiang et al. 2001), this corresponds to a dead zone radius of ~5 AU. We therefore find that, if one just considers the effect of dead zones on the disc structure, and hence on the migration rate, then the migration rate is unaffected, even if the mass fraction in metals is changed from $Z = 1$ to $Z = 0$.

2.2   Disk structure and metallicity

We now consider whether a change in metallicity leads to a sufficient change in disc structure that the disc inflow timescale, τ_ν, and hence the planet migration rate, changes significantly. Since the disc models of Chiang & Goldreich (1997) are static, they are not suitable for this purpose. Ideally, one would like to consider a time-dependent model of a proto-planetary disc when its mass has reached the relevant value (of a few Jupiter masses at ~5 AU). However, for simplicity and to get some indication of the sensitivity of the disc structure to metallicity, we use the disc models of Bell et al. (1997), who consider the detailed disc structure for a variety of values of steady accretion rates. In these models no account is taken of the possibility of "dead zones," and the viscous process is parameterized using the usual α-prescription (Shakura & Sunyaev, 1973). Recent calculations by Fleming & Stone (2003) indicate that this might in fact be a reasonable approach. Their model with an accretion rate of $\dot{M} = 10^{-8} \ \text{M}_\odot \ \text{y}^{-1}$ has a surface density of $\Sigma \approx 140 \ \text{g cm}^{-2}$ at a radius of 5 AU. Thus the mass of the disc at this radius is of order a few Jupiter masses, as

required. What is relevant for our purposes is the viscous inflow timescale given by (Pringle 1981)

$$\tau_\nu \sim R^2/\nu \ \ ,$$

where $\nu \approx \alpha c_s^2/\Omega$ is the viscosity. The Bell et al. (1997) models assume that the dimensionless viscosity parameter is $\alpha = 0.01$. Thus at a given radius, $\tau_\nu \propto T^{-1}$, the midplane disc temperature. In the same model the (optically thick) disc temperature at $R \sim 5$ AU is $T \approx 30$ K. In this temperature range, Bell et al. (1997) find, using Henning & Stognienko (1996), that the opacity is approximately of the form $\kappa = \kappa_o T^{2.1}$, and that $T \propto \kappa_o^{0.34}$. Since at these temperatures the opacity is predominantly due to dust (Pollack et al. 1994; Henning & Stognienko 1996), and although there may be complications due to the detailed structure of the dust and the associated chemistry, it seems reasonable as a first approximation to assume that κ_o, is proportional to the metallicity, i.e. $\kappa_o \propto Z$. In this case a change in metallicity by a factor of ~ 10 leads to a corresponding change in the inflow timescale, and hence migration timescale by a factor of ~ 2.

3   DISCUSSION AND CONCLUSIONS

The observed correlation between the metallicity of a star and its probability for hosting a planet seems to indicate that metallicity is an important factor in planet formation. However, the sample of detected extrasolar planets suffers from obvious selection effects (e.g. Zucker & Mazeh 2001; Tabachnik & Tremaine 2002; Lineweaver & Grether 2002; Armitage et al. 2002). In particular, radial velocity techniques have almost no sensitivity to planets with orbital periods longer than the duration of the survey. Consequently, if the migration process can be inhibited in the low metallicity systems, this would clearly produce a correlation of the type that has been observed.

In the present work, we have therefore examined potential effects of low-metallicity on migration. By considering the basic physical processes involved, we have shown that in low-metallicity systems, migration could be slowed down, but at most by a factor ~ 2 (in terms of timescale). Such a modest sensitivity is not expected to produce the observed rise in probability for hosting a planet (Armitage et al. 2002 have considered models in which the viscous timescale was changed by similar factors, with no significant consequences for the resultant orbital distribution). Therefore, our tentative conclusion is that the metallicity observations do support the idea that a higher metallicity is associated with a higher rate of *formation* of planets rather than with migration. Our conclusion is further supported by the fact that there is no distinguishable difference in metallicity between the stars hosting planets with semi-major axes longer than the observed median, and those with shorter ones (Fischer & Valenti 2003). To make this conclusion ironclad would require a detailed, time-dependent, migration computation, that would include a full treatment of the thermal structure of the disc.

It is interesting to note that the non-detection of transiting planets in the globular cluster 47 Tuc (Gilliland et al. 2000) is entirely consistent with the dependence of hosting a planet on metallicity. Originally, Gilliland et al. estimated an expected number of 17 detections (from monitoring 34,000 stars). If one takes account, however, of the fact (Marcy et al. 2003) that only 0.6% of the F, G, K, M stars in the solar neighborhood have "hot Jupiters" (giant planets with orbital periods $P < 5$ days; Gilliland et al. assumed 1%), and the dependence of probability on metallicity, the number of expected detections is reduced to ~ 2.

If the formation of planets indeed requires metals, one needs to explain the recent observation of a planet in the globular cluster M4 (Sigurdsson et al. 2003). That cluster has a metallicity that is only 5% that of the sun, and therefore the formation of planets in it would be expected to be suppressed. It is important to note, however, that even in such a low metallicity environment, there are circumstances where dust and metals are abundant. One example is supernovae (note that the planet in M4 is a companion to the pulsar B1620−26), which can produce copious amounts of dust (2–4 solar masses in the case of Cas A; Dunne et al. 2003). Another dust-rich environment is around asymptotic giant branch stars. In fact, the white dwarf companion to the pulsar B1620−26 had to evolve through such a phase. It is not impossible that the circumbinary planet was in fact formed during that phase (and not around a main sequence star, as suggested by Sigurdsson et al.), and it was later pushed via interactions into a non-coplanar orbit. Finally, planets around pulsars (or white dwarfs) can form from the disruption of white dwarf companions (Livio, Pringle & Saffer 1992; Podsiadlowski et al. 1991).

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